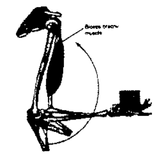
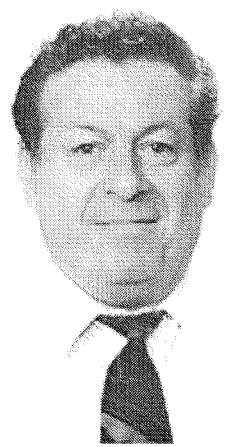


Electroactive polymers (EAP) as Emerging Technology for Devices and Robotics

Review, Capabilities, Applications and Potential



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Outline

- Background
- What are the alternative
- Robotics and EAP
- Longitudinal and bending EAP
- Current planetary applications
- Emerging technologies to support the EAP infrastructure
- Future development and applications

What is an Electroactive Polymer (EAP)

- EAP materials are polymers that exhibit change in a property or a material/physical characteristic as a result of an electrical stimulation (field, current, etc.).

- Changes can involve physical deformation, optical or magnetic variation and others.

- The emphasis of this course is on EAP materials that display electro-mechanical reaction.
  - The majority of the course material will focus on actuation capabilities.
  - Sensing will be discussed mostly in relation to IPMC materials.

Background

- Electroactive polymers (EAP) are emerging with behavior that mimic biological muscles.

- These materials can be used to produce actuators that are miniature, light, inexpensive, miser and best of all large displacement inducers.

- Tests have shown that certain EAP materials operate effectively also at cryogenic temperatures and vacuum.

- The technology enables unique actuation to support various mechanisms, robotics and locomotion needs.

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Alternative electroactive materials

- For many years, the leading actuation materials have been electroactive ceramics (EAC) and shape memory alloys (SMA).

- In contrast to EAC, EAP are emerging with >2 orders of magnitude displacement capabilities that cannot be matched by the striction-limited, rigid and fragile ceramics.

- In contrast to SMA, EAP responds significantly faster and have fatigue life many orders of magnitude longer.

- EAP are more compliant to mass-production, easy to configure in various shapes and potentially can be made at low cost.

Comparison between EAP and widely used transducing actuators

Property	EAP	EAC	SMA
Actuation strain	>10%	0.1 - 0.3 %	<8% short fatigue life
Force (MPa)	0.1 – 3	30-40	about 700
Reaction speed	μsec to sec	μsec to sec	sec to min
Density	1- 2.5 g/cc	6-8 g/cc	5 - 6 g/cc
Drive voltage	1-7V/ 10-100V/μm	50 - 800 V	NA
Consumed Power*	m-watts	watts	watts
Fracture toughness	resilient, elastic	fragile	elastic

* Note: Power values are compared for documented devices driven by such actuators.

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Historical prospective

- The pioneering of the EAP field can be attributed to Eguchi's 1925 reported discovery of an electret material*.
  - Obtained when carnauba wax, rosin and beeswax are solidified by cooling while subjected to DC bias field.

- Another important milestone is the 1969 observation of a substantial piezoelectric activity in PVF2.
  - PVF2 films were applied as sensors, miniature actuators and speakers.

- Since the early 70's the list of new EAP materials has grown considerably, and the most progress was made in this decade.
  - This EAPAD conference of SPIE, initiated by its Chair, is the first conference on this subject.

- Even though many EAP were already introduced, the number of commercially used ones was mostly limited to PVF2/TRFE materials and ceramic/ polymer composites.

* Electrets are dielectric materials that can store charges for long times and produce field variation in reaction to pressure.

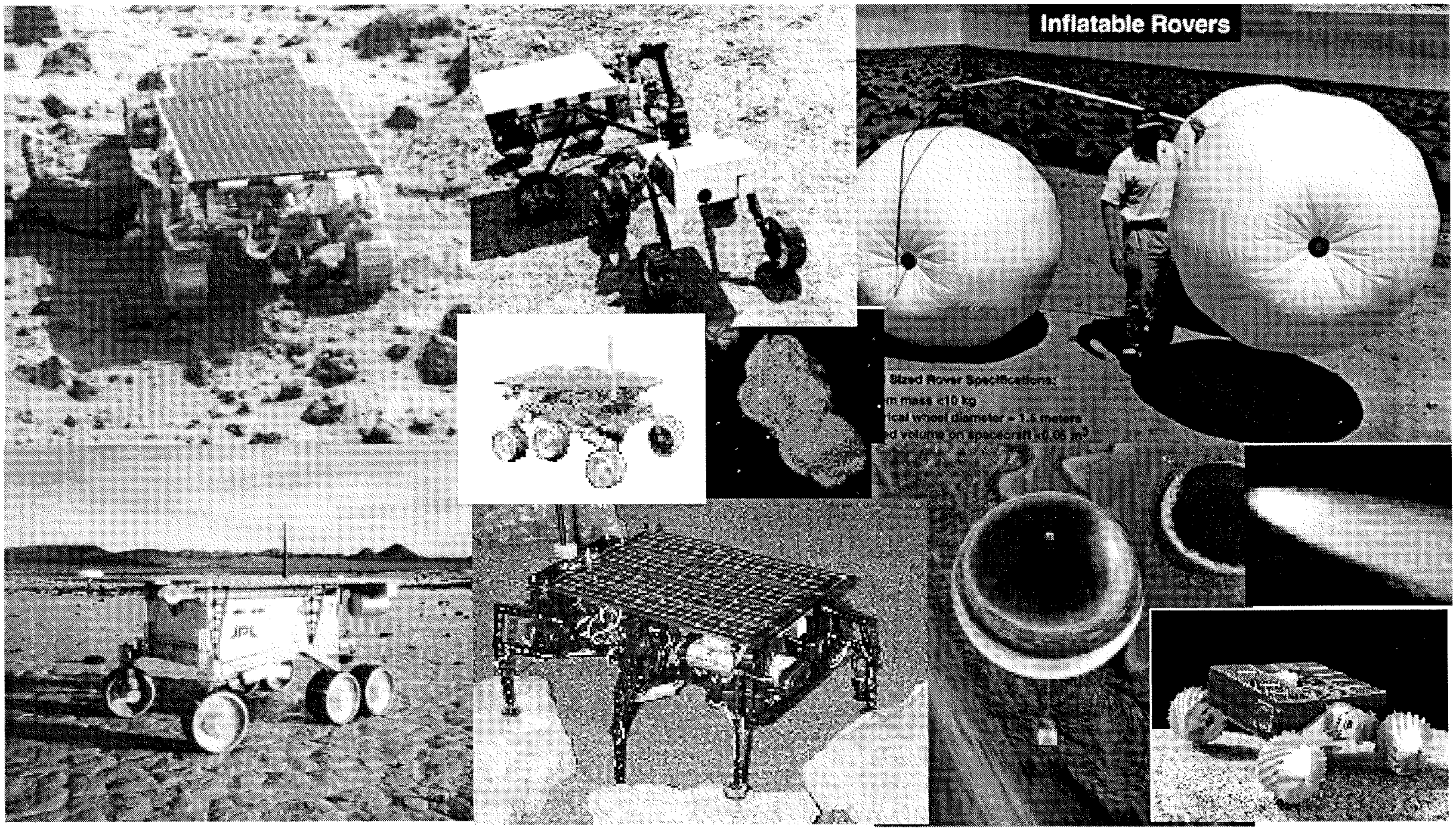
The evolution of EAP

- The large-displacement actuation combined with other attractive characteristics (light, resilient, consume low-power, long fatigue life, low cost and rapid respond) offer incentives to pursue their application.

- Some of the leading emerging EAP materials are:
  - Electro-Statically Stricted Polymers (ESSP) exhibiting several tens of percents actuation strain.
  - Ionic-gel demonstrating over 50% contraction.
  - Ion-exchange Polymer membrane Metal Composites (IPMC) bending close to 90°.

- Even though some of these materials offer actuation displacement capabilities that are similar or exceed the performance of biological muscles, their force actuation is relatively small.

Rover technology at JPL



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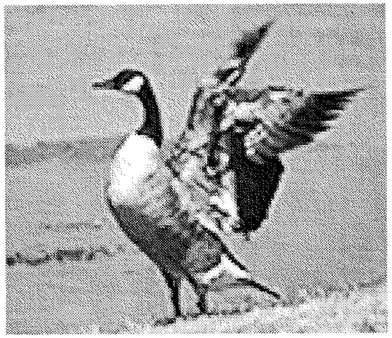
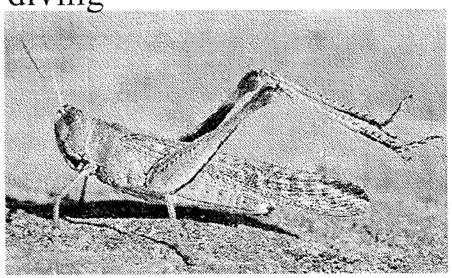
Biological models for EAP actuated flexible robots

Multiple locomotion capabilities

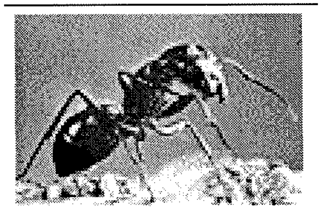


Flying, walking, swimming & diving



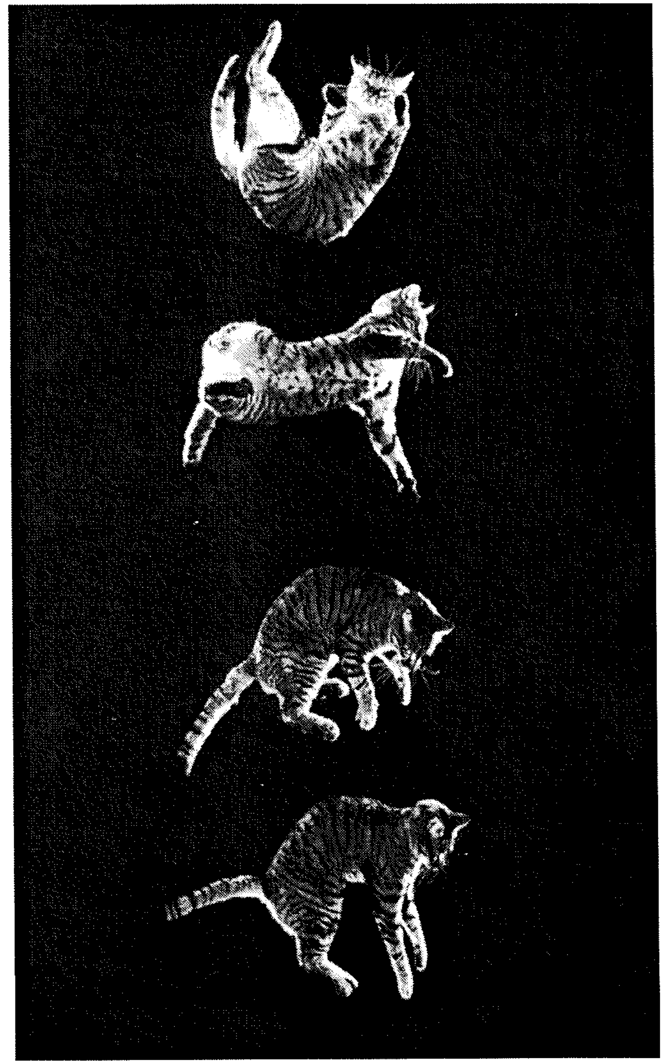
Hopping, flying, crawling & digging

Coordinated robotics



Examples from nature offer ideas for scalable autonomous robots that can be used to colonize planets and perform multi-tasking in-situ exploration missions

Soft landing



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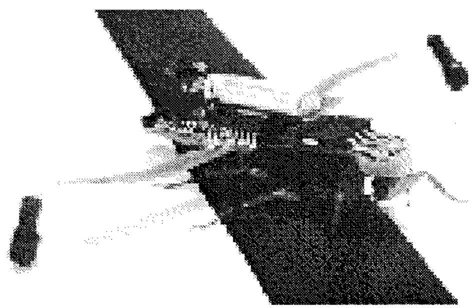
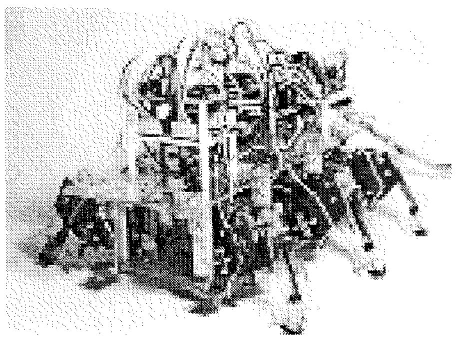
Insects as workhorses and robots

- Insects were used by various researchers (e.g., University of Tokyo, Japan) as locomotives to carry backpack of wireless electronics.

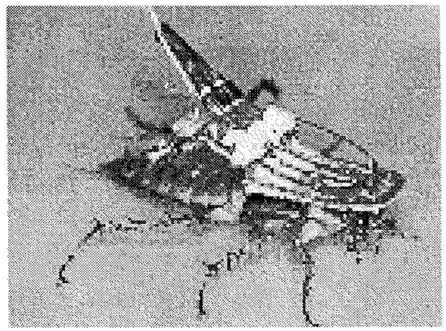
- EAP offers the potential of actuating insect-like robots to replace the "real thing".



Cricket



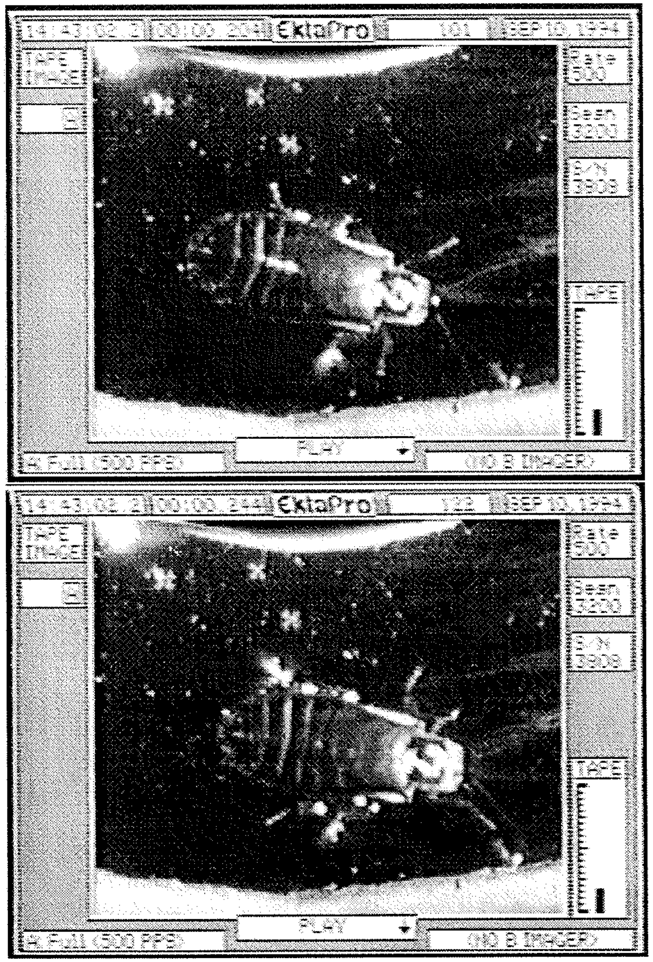
Spider



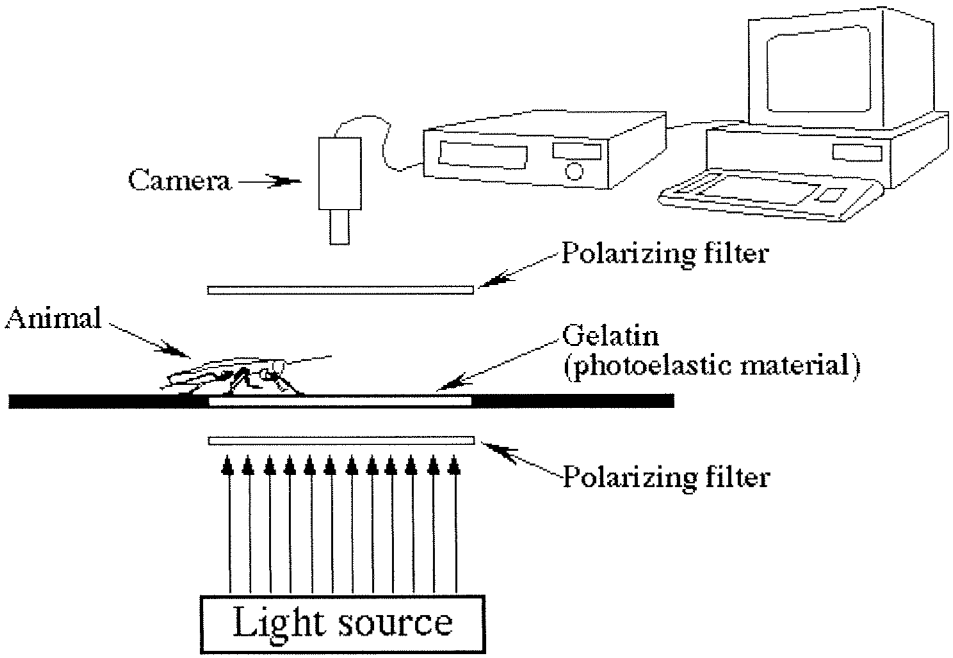
Cockroach

Reference: http://www.leopard.t.u-tokyo.ac.jp/

Insect walking process*



Photoelastic force platform is used at Berkeley to study insect walking mechanism.



* Robert Full, Berkeley U.
Ref: http://rjf2.biol.berkeley.edu/Full_Lab/FL_Publications/PB_Posters/94ASZ_Turning/94ASZ_Turning.html

Potential EAP applications for robotics

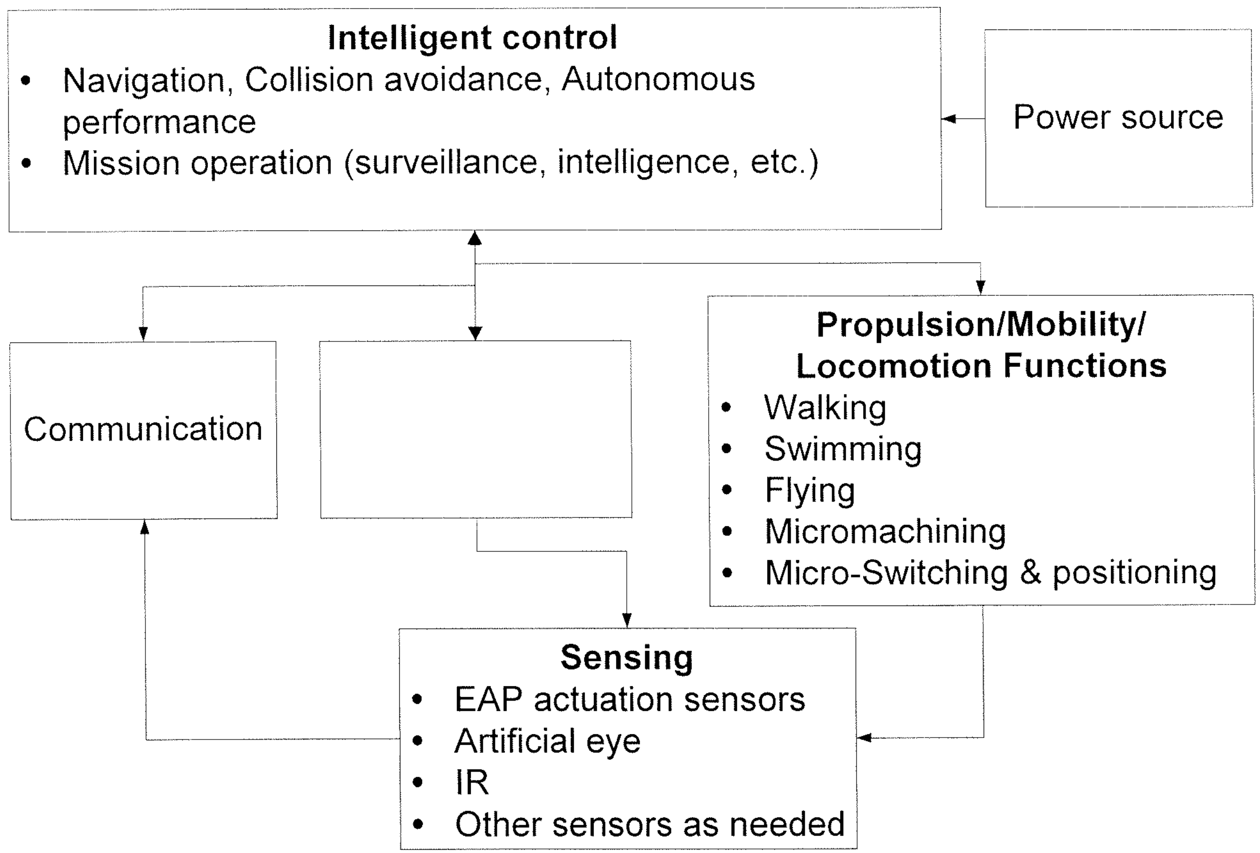
- EAPs offers unique characteristics to produce highly maneuverable, noiseless, agile biomimetic miniature robots.

- EAP actuators can be used to produce mechanisms with simple drive signals but the nonlinear behavior needs to be taken into account.

- Such materials can be used to provide the necessary locomotion drive mechanism of insect-like (flying, crawling, swimming, etc.) robots at sizes that range from microns to several centimeters.

- The development and application of EAP materials and mechanisms involves interdisciplinary expertise in chemistry, materials science, electronics, mechanisms, computer science and others.

Elements of an EAP actuated system



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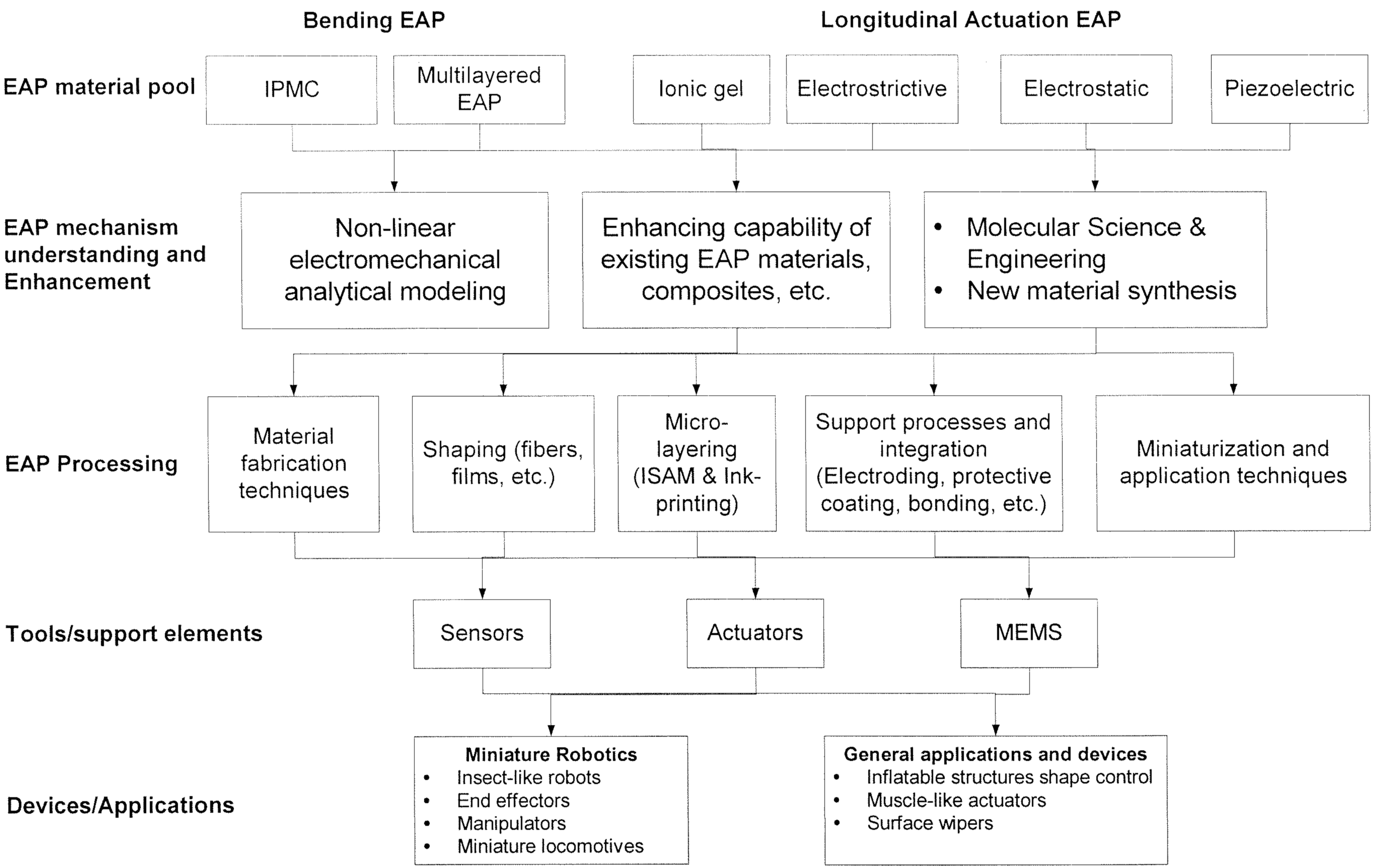
EAP infrastructure



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Technology status

- Bending and longitudinal EAP actuators are developed by numerous research institutes, academia and industry.
- Various unique capabilities and applications are investigated.
- EAP changed the paradigm about robotics construction - polymer materials can serve simultaneously as a structural element, actuator and end-effector.
  - Conventional robots are driven by mechanisms that consist of motors, gears, bearings, etc.
  - Electroactive polymers (EAP) offer alternative simple and direct actuation with resilience and toughness emulating biological muscles.
- The potential for space, medical, commercial, military and other applications are great but the main limiting factor is their low force actuation capability.

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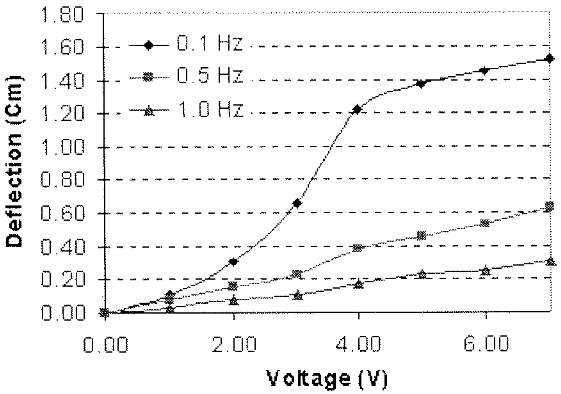
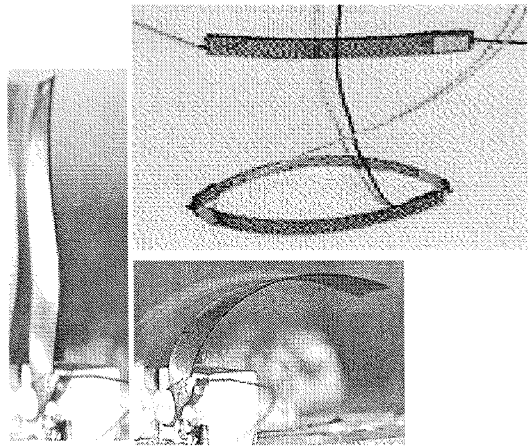
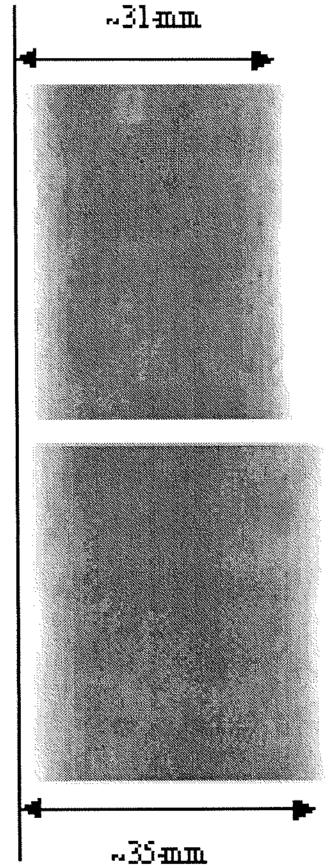
Bending and longitudinal EAP

examples





Ion-exchange Polymer membrane Metallic Composite (IPMC) can bend by over 90° under ~3-4V and ~30-50-mW.



31-mm wide, 50-μm thick Electrostatically stricted polymer (ESSP) film extending over 12%

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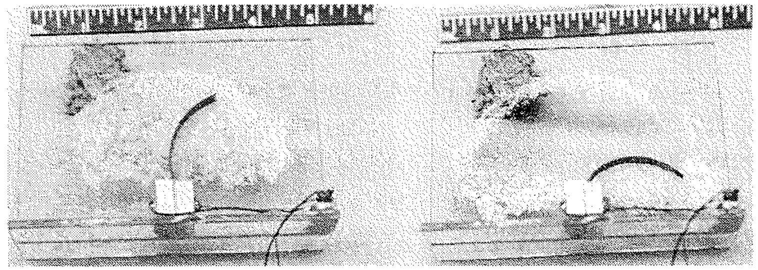
EAP mechanisms developed at JPL

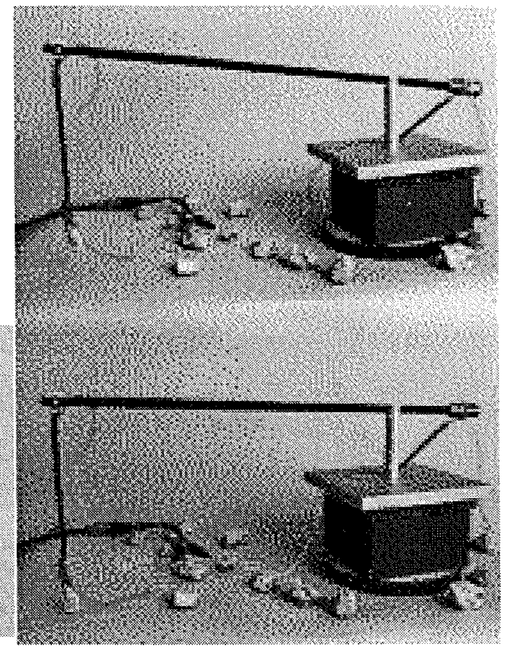
Dust wiper

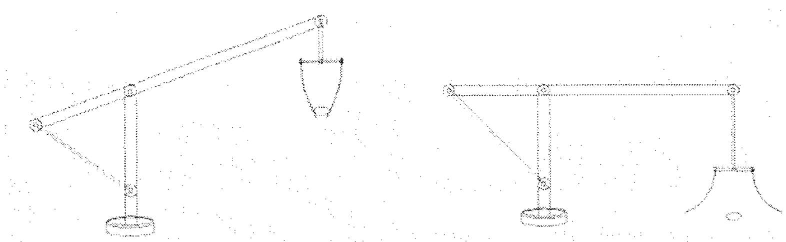
A bending EAP is being developed as a dust wiper for application considerations in the MUSES-CN mission

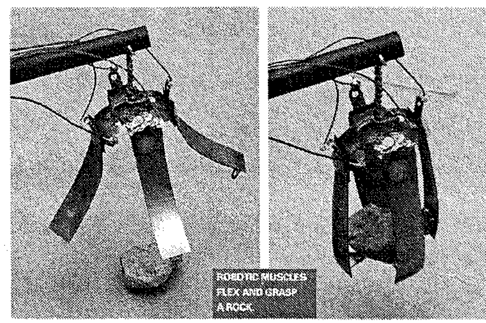


Miniature robotic arm

A stretching EAP is used to lower a robotic arm, while bending EAP fingers operate as a gripper. The technology is being developed to enable miniature sample handling robotics.







Discover Magazine, Aug. 98, p.33

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Longitudinal EAP Actuators
Electro-Statically Stricted Polymer (ESSP)

- Polymers with low elastic stiffness and high dielectric constant can be used to induce large actuation strain by subjecting them to an electrostatic field.
- Coulomb forces between electrodes can squeeze or stretch a sandwiched polymer material.
- Longitudinal electrostatic actuator can be made of a dielectric elastomer film (silicone) coated with carbon powder electrodes.
  - The force (stress) that is exerted on such a film with compliant electrodes is:

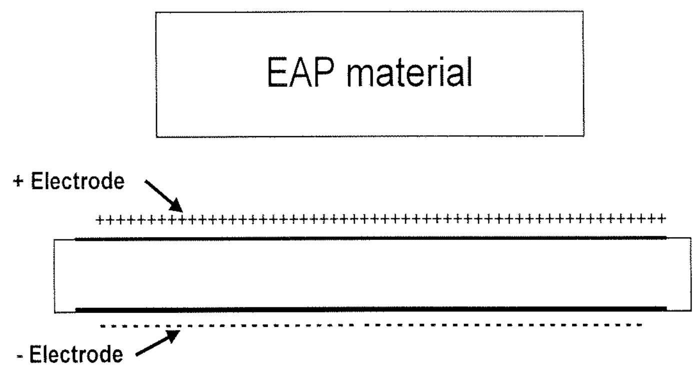
$$P = \varepsilon\varepsilon_0 E^2 = \varepsilon\varepsilon_0 (V / t)^2 \qquad (1)$$

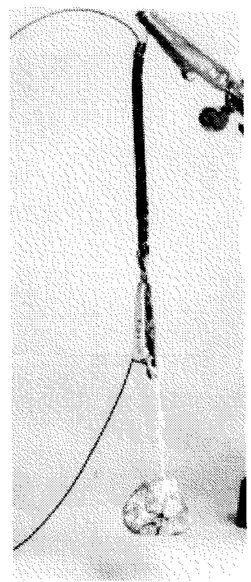
Where: P is the normal stress, ε_0 is the permittivity of vacuum and ε is the relative permittivity (dielectric constant) of the material, E is the electric field across the thickness of the film, V is the voltage applied across the film and t is the thickness of the film. The Poisson's ratio is assumed as 0.5.

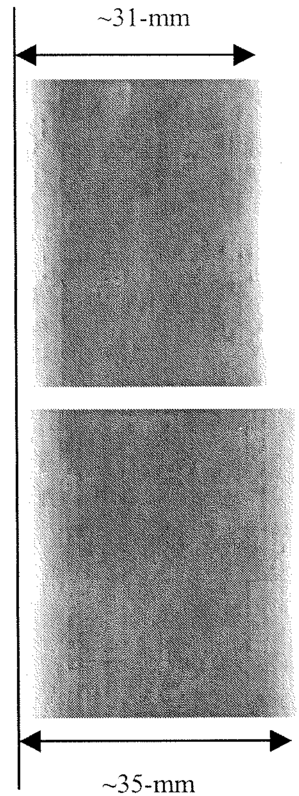
Longitudinal eap actuator

Electro-Statically Stricted Polymer (ESSP)

Under electro-activation, a polymer film with electrodes on both surfaces expands laterally.







EAP film subjected to 25 V/μm induced over12% extension

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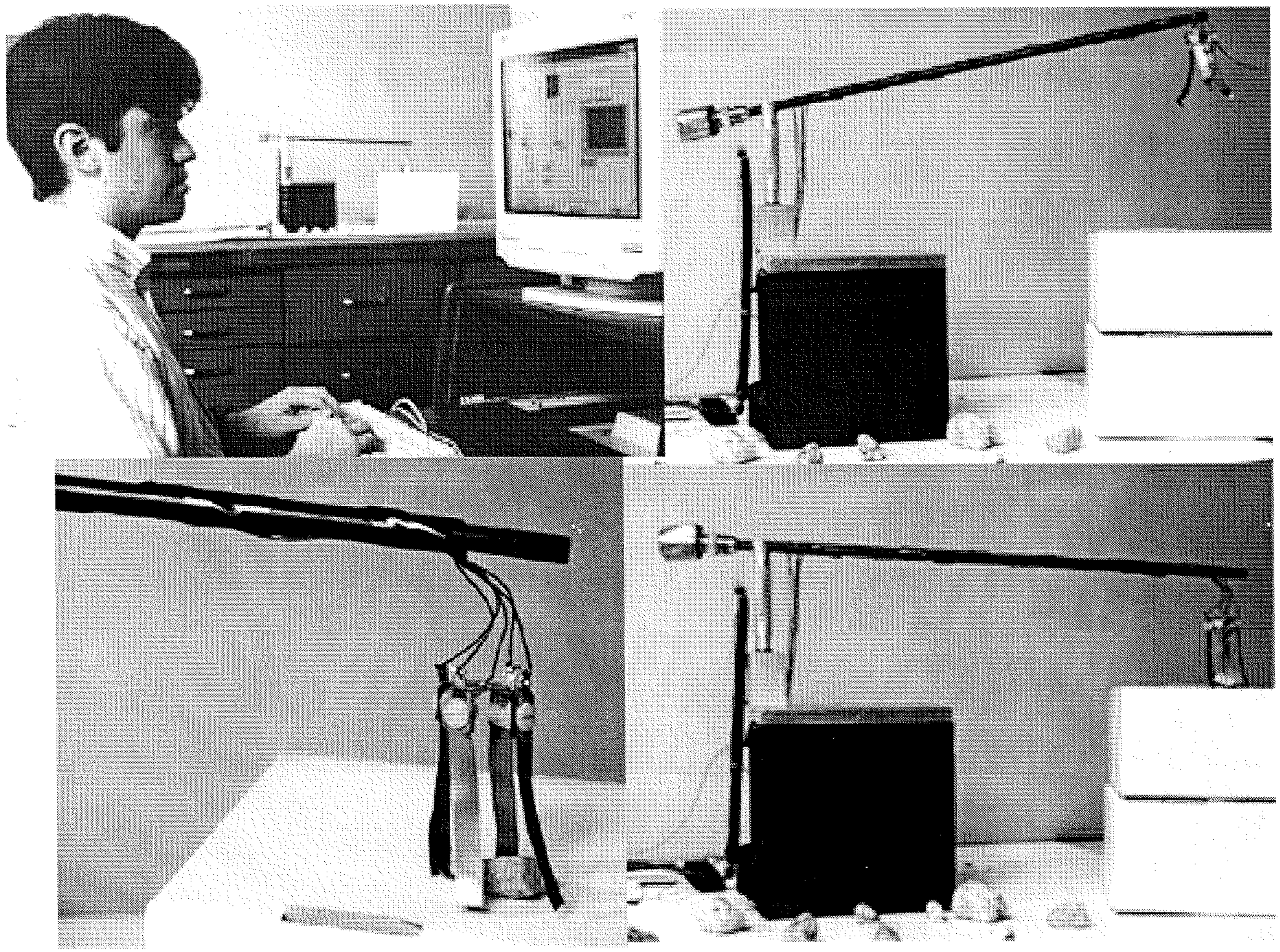
Robotic arm

A computer controlled arm with longitudinal EAP actuator serving as the lifter and bending EAP fingers as the gripper



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Electro-Statically Stricted Polymer (ESSP)

- Polymers with high dielectric constants and application of high electric field leads to large actuation forces and strains.
  - Under an electric field the film is squeezed in the thickness direction causing expansion in the transverse direction.
  - For a pair of electrodes with circular shape, the diameter and thickness changes can be determined using the following relation, where the second order components are neglected.

$$\Delta D / D_0 = -(1/2)\Delta t / t_0 \tag{2}$$

Where: D_0 is the original diameter of the electrodes and ΔD is the resultant diameter change, t_0 is the original thickness and Δt is its change under electric activation.

- Enhancement of the actuation capability is expected from electrostrictive polymers. Such polymer offers, in addition to the effect of the Coulomb forces, also inherent contraction of the polymer.

Bending EAP actuator/sensor

Capabilities

- IPMC induces large bending actuation strain
- It also induce the reverse phenomena, i.e., sensing bending strain
- Effective at low temperatures (-100°C) and vacuum (1-torr)
- Unique electrical resistance that grows with the decrease in temperature
- Capacitive behavior that is employed for power storage

Limitations

- Requires coating to prevent loss of the ionic content when operating in air
- Coating process involves wrinkling, blistering, off-axis bending and non-linear deformation
- Transverse deformation constrains the response
- Low actuation force
- Slow response to turn-off, retraction under DC-voltage and degrades by electrolysis at >2V
- Complex equivalent circuit characteristics

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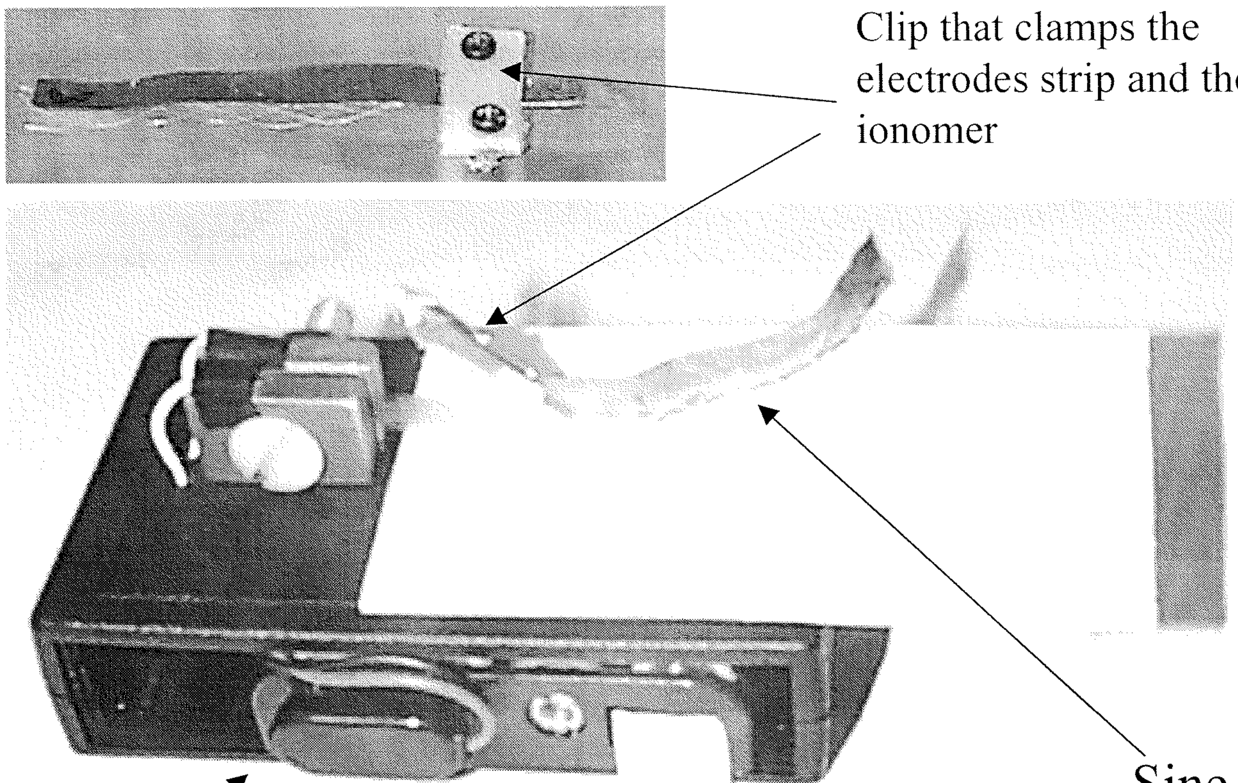
Surface Wiper Setup



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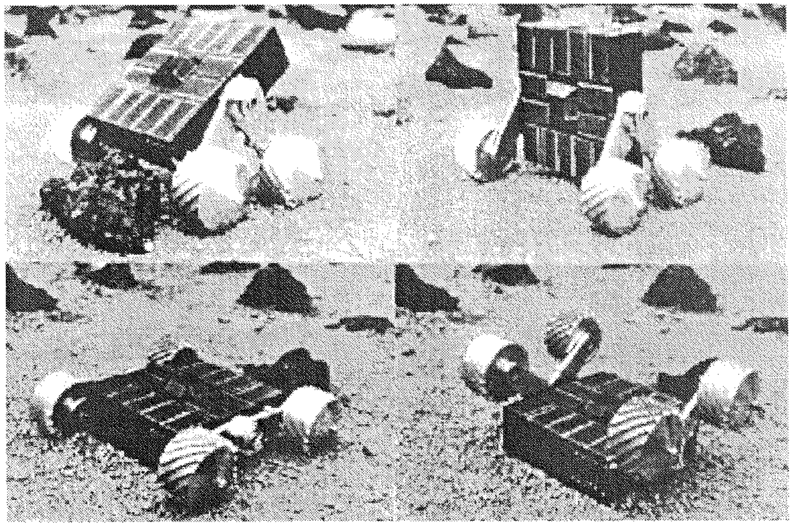
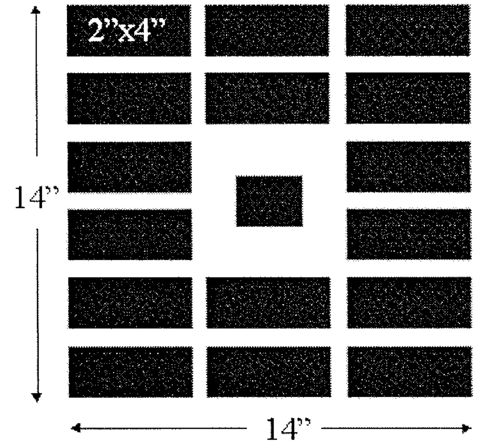
Planetary technical challenges



NanoRover



Solar cells layout

- Mars exploration requires removal of dust as small as 3.2μm diameter.

- Operation on an asteroid (MUSES-CN mission) requires addressing the effect of ionic radiation, UV and a large temperature range.
  - Overall the temperature range is: -155°C to +125°C and the desired operating range is -125°C to + 60°C

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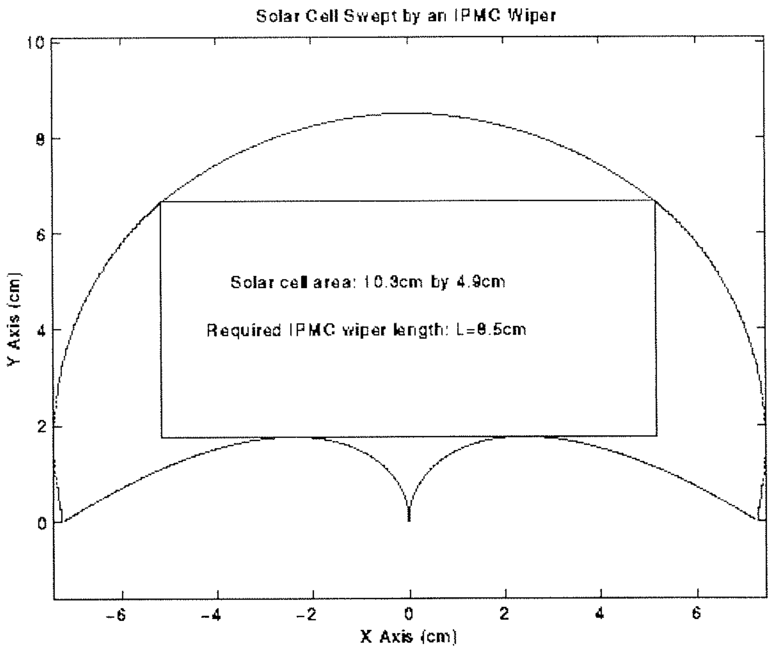
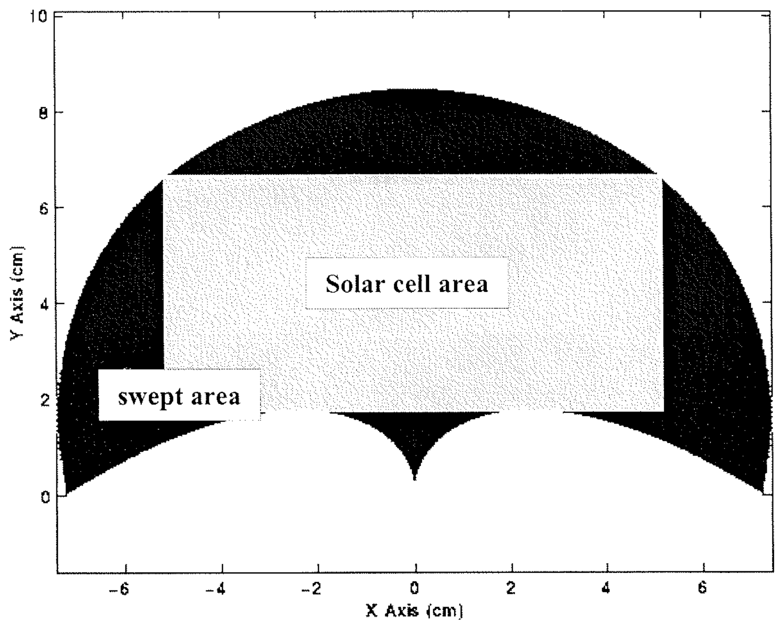
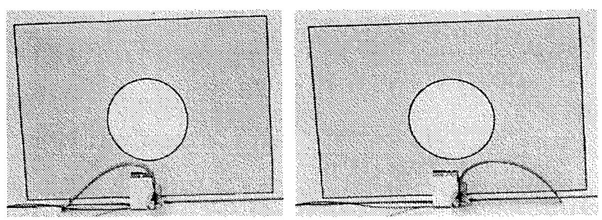
Surface wiper using bending EAP

Using best fit wiper curving characteristics for a 103mmX49mm area





Actual bending



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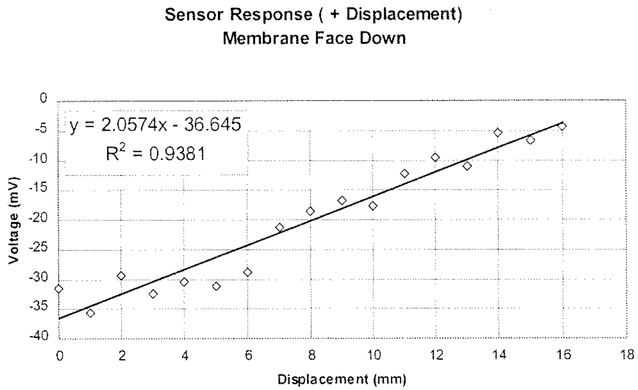
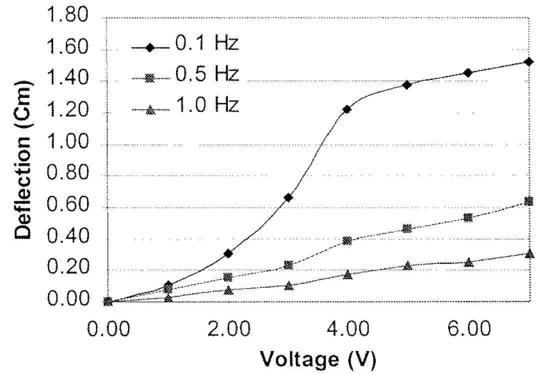
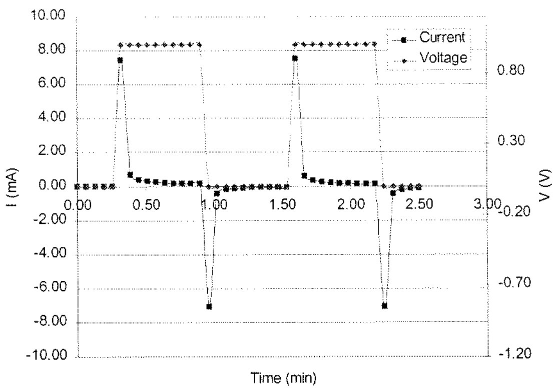
EAP bending actuator/sensor



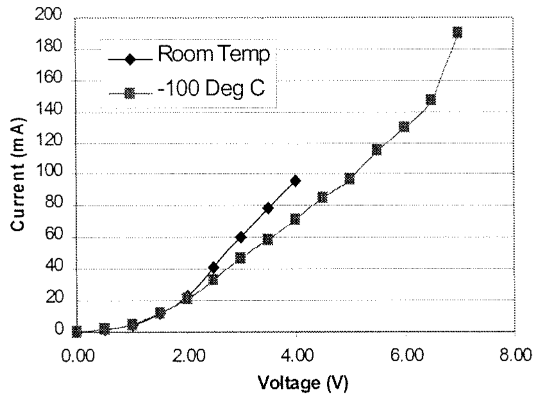
Sensor (Shahinpoor, UNM data)



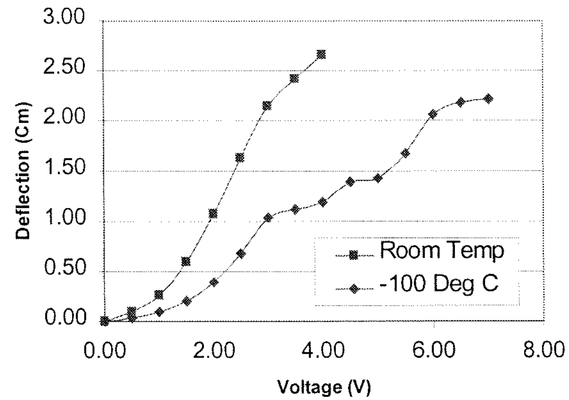
Actuator



Charging capability



Higher resistance at Low Temp



Response at Cryovac

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EAP as breakthrough technology

- In May 1998, the EAP technology was selected by the JPL management as "one of the potential breakthrough technologies, which have great promise in enabling JPL's exciting new missions through and beyond the next decade".

- In its August 98 issue, under the category Breakthrough Technology, Discover Magazine covered the JPL led EAP activity in an article entitled "Bendbots".

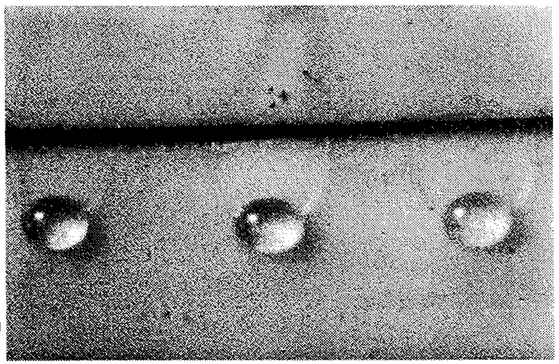
Enhancement issues

- One of the major shortcomings of EAP is their relatively low force actuation capability, falling way shorter than biological muscle.

- To enhance the actuation force, materials science and electromechanics as well as engineering issues require adequate attention.
  - Computational chemistry modeling is needed to allow methodic design and synthesis of new effective EAP materials.
  - Comprehensive mechanics modeling is needed to analyze the non-linear behavior.

- The processes of synthesizing, fabricating, electroding, shaping and handling EAPs needs to be refined to maximize EAP's actuation capability and robustness.

Inkprint bonding of a sine-shape wire blade (by MicroFab)



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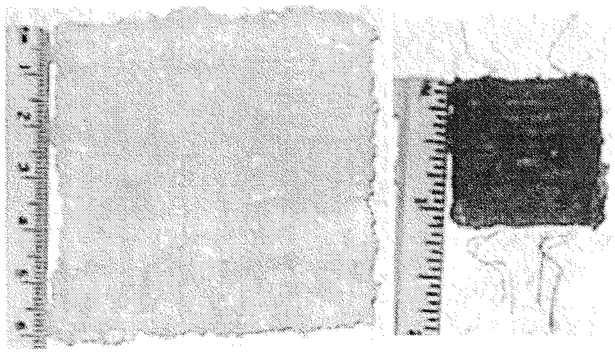
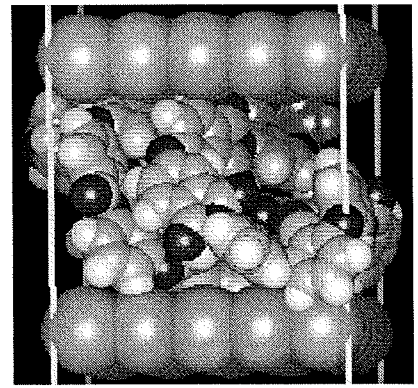
Emerging EAP materials and processes

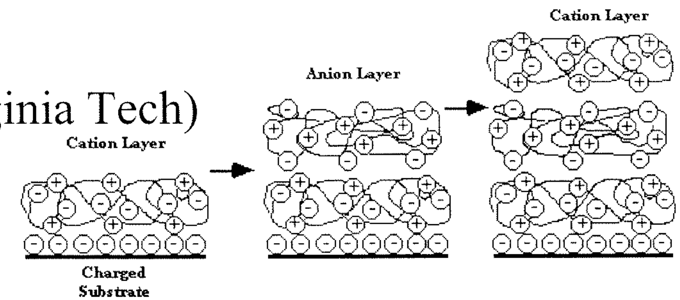
Alternative EAP:
Ionic gel EAP
(U. of Arizona)



Design tools:
Computational
chemistry
(NASA LaRC)

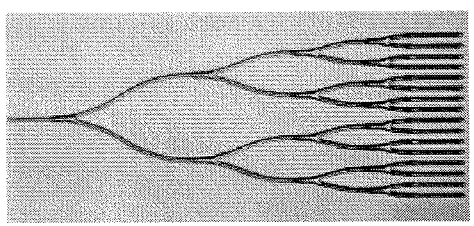


Ionic self-assembled mono-layering (Virginia Tech)

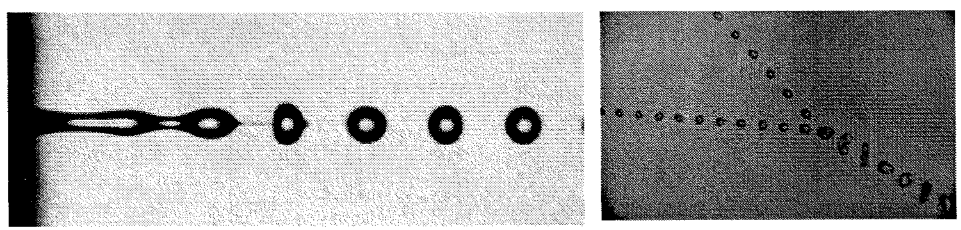


Micro-fabrication techniques (MicroFab):

Ink-printing



100-µm Waveguide



50-µm drops jet

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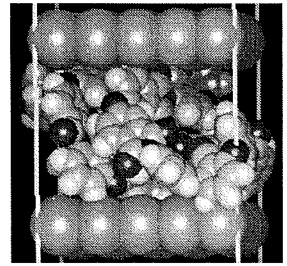
FEM Computational chemistry of EAP



- The improvement of the induced force capability of EAP is critical to making these materials the actuators of choice.
- Recent work at the NASA LaRC's Computational Materials Program used accurate quantum chemistry calculations to determine force fields for a range of polymers including polyimides.
- The calculated force field was experimentally verified (through thermo-physical and ultrasonic measurements).
  - The method was used to predict response to electric fields, mechanical stresses, and temperature.
- Planes of large spheres represent the metal electrodes, and are used to simulate the poling field. The properties from atomistic simulations are fed into large-scale finite-element models.
- So far, successful models at the atomistic, micro-mechanical, and continuum levels have been developed.

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Modeling EAP large strain actuation

- Effective design of EAP mechanisms with large actuation strains, requires analytical tools that can address the nonlinear behavior.
- Generally, the constitutive relations for electroactive materials can be adequately described by means of equations of the form:

$$D_i = \varepsilon_{ij} E_j + 2m_{ijkl} E_j \sigma_{kl}, \qquad e_{ij} = m_{ijkl} E_k E_l + s_{ijkl} \sigma_{kl}$$

Where: **D** is the electric displacement vector, **E** is the electric field vector, **e** is the strain tensor and σ is the stress tensor. The coefficient matrices and tensors of the equation are material constants that need to be determined through laboratory tests.

- The mechanical response to a given electrical field is determined from a suitable equation of motion supplemented by these constitutive relations.
- A distinguishing feature of electrostrictive materials is the presence of the nonlinear (quadratic) terms in **E**.

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Modeling EAP large strain actuation (Cont.)

- The constitutive equations are linear in the strains and, therefore, can only be used to analyze "small displacement" actuators.
- Certainly, EAP strain is not "infinitesimal," and the quasi-linear constitutive relations may not be adequate to predict the electro-mechanical behavior.
- An alternative system of constitutive relations is needed that includes the nonlinear terms in the strain and the electric fields.
  - The nonlinear constitutive relations needs to contain quadratic terms in both **E** and **e** based in thermodynamic principles.

Significant future applications

Mechanisms & Robotics

Muscle actuators that are resilient and damage tolerant will enable:

- Walking, crawling, swimming and/or flying miniature robots
- Insect-like robotic colonies that emulate ants.

Miniaturization

MEMS using EAP actuators and sensors.

Planetary applications

Recent JPL results, showing that bending-EAP are operating at low-temperatures and vacuum, have a great promise for space applications such as:

- EAP surface wiper for dust removal from optical/IR windows
- Miniature robotic arm for sample manipulation
- Under consideration: Support active/controllable inflatable structures

Transition to broad range of applications

Beneficiaries include: medicine, consumer products and military.

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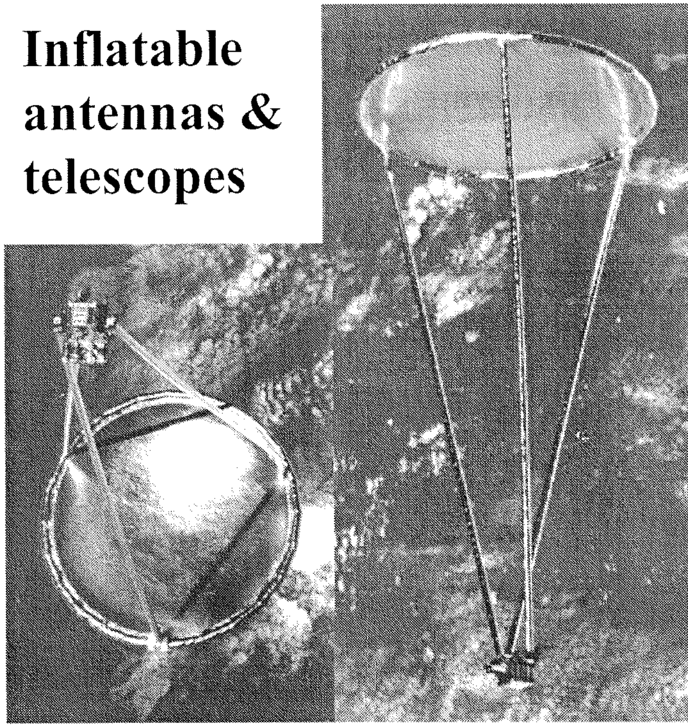
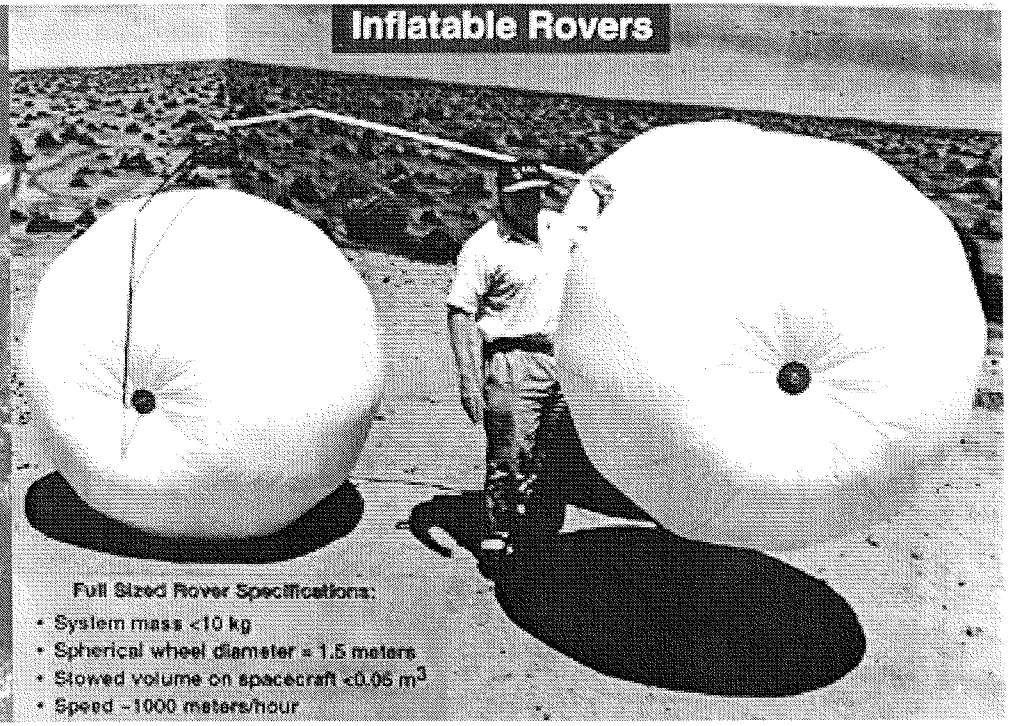
Inflatable structures

Inflatable antennas & telescopes



Inflatable vehicles



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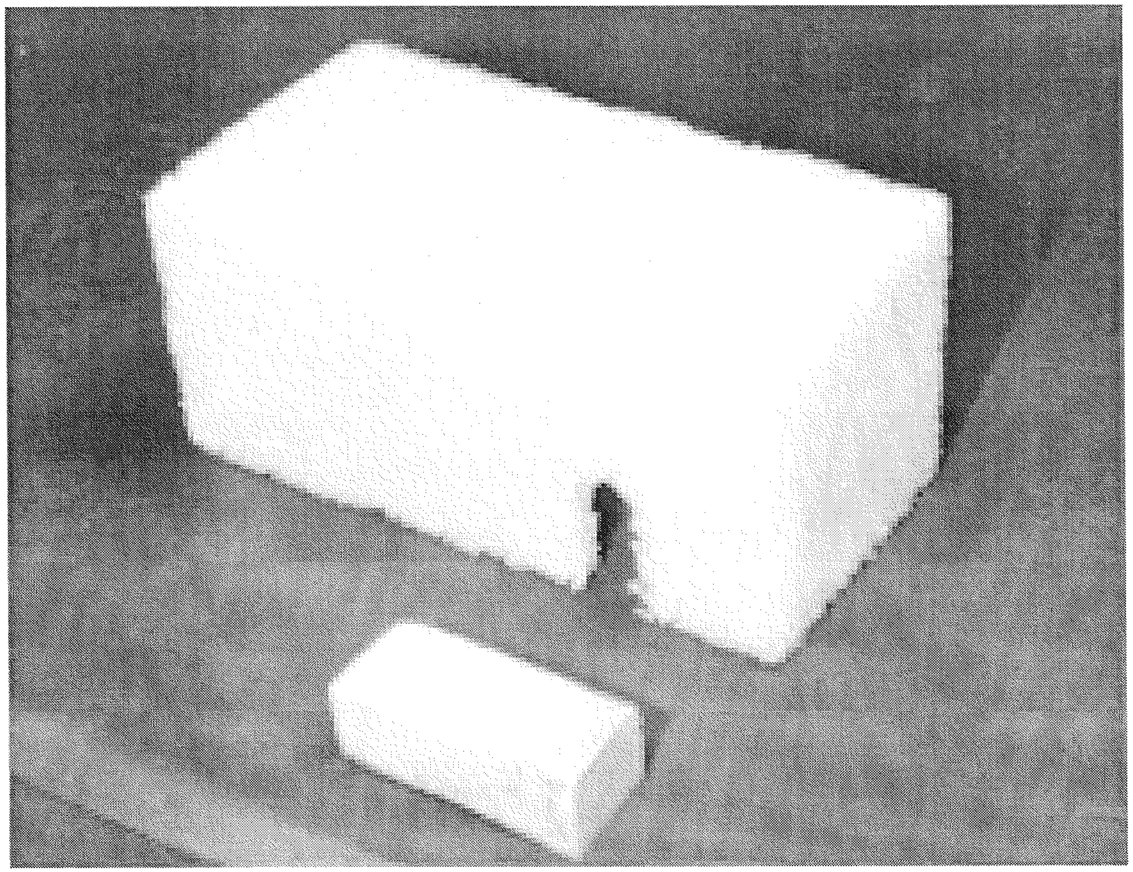
Shape Memory Polymers*

Restored Structure



Compacted Structure

* W. Sokolowski, JPL, 1999

Summary

- Electroactive polymers (EAP) are emerging with capabilities that mimic biological muscles.
  - Inducing large displacements and can be made miniature, low mass, inexpensive, and consume low power.

- The technology enables unique actuation for various mechanisms, robotics and locomotion capabilities.

- The infrastructure of the field needs to be enhance and international collaboration among the developers and users is expected to lead to great improvement in the coming years.
  - Issues associated with their low force actuation capability and non-linear behavior requires attention.
  - Effective sensors are needed to track the large displacement as well as provide position information.
  - The resilience of the material and flexibility of the material poses control problems